The Effect of Haptic Degrees of Freedom on Task Performance in Virtual Surgical Environments

Jonas FORSSLUND [a,1], Sonny CHAN [a,1], Joshua SELESNICK [b], Kenneth SALISBURY [a,c], Rebeka G. SILVA [d], and Nikolas H. BLEVINS [b]

[a] *Computer Science Department, Stanford University*
[b] *Department of Otolaryngology, Stanford University*
[c] *Department of Surgery, Stanford University*
[d] *Oral & Maxillofacial Surgery Section, VA Medical Center, San Francisco*

Abstract. Force and touch feedback, or haptics, can play a significant role in the realism of virtual reality surgical simulation. While it is accepted that simulators providing haptic feedback often outperform those that do not, little is known about the degree of haptic fidelity required to achieve simulation objectives. This article evaluates the effect that employing haptic rendering with different degrees of freedom (DOF) has on task performance in a virtual environment. Results show that 6-DOF haptic rendering significantly improves task performance over 3-DOF haptic rendering, even if computed torques are not displayed to the user. No significant difference could be observed between under-actuated (force only) and fully-actuated 6-DOF feedback in two surgically-motivated tasks.

Keywords. surgical simulation, haptics, haptic rendering, task performance

1. Introduction

What degree of haptic fidelity must a surgical simulator have in order to optimally achieve its objective? The inclusion of force and touch feedback, or haptics, plays a significant role in the realism of many virtual reality surgical simulations. Research in novel haptic interfaces and force rendering algorithms has continued to enhance the fidelity of instrument control and manipulation in surgical simulators. While it is clear that sophisticated devices and rendering techniques can deliver a more realistic experience, they may do so at prohibitive financial or computational expense. Additional effort is still required to improve our understanding of the impact of haptic fidelity on the efficacy of virtual reality simulators [1,2]. In the present work, we specifically examine consequences for task performance of using different numbers of degrees of freedom (DOF) of force feedback.

Laparoscopic surgery simulators are currently the most mature application of virtual reality surgical simulation, and this specialty appears to be the one for which the role

[1] These authors contributed equally to this work. Correspondence to: Stanford BioRobotics Laboratory, 318 Campus Drive, Stanford, CA 94305; E-mail: sonny@cs.stanford.edu

of haptic feedback has been rigorously evaluated. Studies have shown that haptic feedback improves performance on laparoscopic tasks in a virtual environment [3] and has a positive effect on skills training [1], especially for surgical tasks in which forces play an important role (eg. stretching, grasping, cutting) [4,5].

Little is known about the effect of the quality of haptic feedback on performance. In fact, it is possible that haptic feedback can even be detrimental. For example, learning surgical practices with an unrealistic model can allow the surgeon-in-training to use techniques that would be impossible or even dangerous in real surgery [6], which may even lead to negative training transfer [4,5]. Intuitively, the overall success of a simulator is dependent on how well the haptic feedback reflects relevant real forces experienced by the surgeon while performing the surgical task [2,7].

2. Background

Several authors have begun to investigate the effect of haptic feedback fidelity in various applications. Kim et al. [5] tested two force response models of different accuracy for material elasticity in a laparoscopic surgery simulation. Although they observed that results with an approximate model were similar to the high-fidelity model, laparoscopic surgery involves manipulating constrained instruments that limit the surgeon's haptic sense [2], which makes it more difficult to perceive small differences in force. Wagner et al. performed an experiment to demonstrate the effect of varying degrees of force feedback for a blunt dissection task using a tele-operated robot [8].

Exploring a complex environment using a rigid instrument is a 6-DOF interaction involving both forces and torques. Wang and Srinivasan first attempted to characterize the role of torque feedback on a subject's ability to determine a virtual object's distance through making contact with a long, thin rod [9]. Verner and Okamura designed a simple tracing and drawing task where the subject used a virtual pencil with varying combinations of force and torque feedback [10]. They found that, for such a task, force feedback significantly improved user performance, but the addition of torque feedback did not yield significant improvement over forces alone. Weller and Zachmann showed that 6-DOF haptic devices outperformed their 3-DOF counterparts in terms of intuitiveness of control and quality of force feedback in a competitive object collection game [11].

Well-known algorithms for haptic rendering are primarily 3-DOF in that they compute output forces based on device position only, and have no concept of orientation or torque. They permit haptic interaction only through a point or a rotationally-invariant sphere. A number of surgical simulators in which the surgeon manipulates a rigid virtual instrument, such as a scalpel or surgical drill, have been developed based on these 3-DOF haptic rendering principles [12,13,14]. In contrast, a 6-DOF haptic rendering algorithm computes both forces and torques from the position and orientation of the device. These methods use the entire virtual instrument's geometry for collision and contact handling.

A common misconception is that use of a 6-DOF haptic rendering algorithm requires a fully-actuated 6-DOF haptic device. Such devices carry a significant cost premium due to mechanical design challenges that need to be overcome and the high cost of parts. Today, many commercially-available haptic devices are asymmetric in that they have a different number of sensors than actuators (motors) [15]. A common kind (e.g. SensAble's Phantom Omni) senses 3D position and orientation (6-DOF), but provides only directional force feedback (3-DOF).

3. Research Questions

As a step toward informing the level of haptic realism and fidelity required to achieve surgical simulation objectives, we study the effect of haptic feedback degrees of freedom on task performance. In minimally invasive surgery or microsurgery, the surgeon must often work through narrow corridors while avoiding excessive force or accidental incursions that can cause trauma to surrounding tissue or sensitive structures [8]. We designed a surgically-motivated interaction task that involves similar precise positioning of a virtual instrument in kinematically constrained environments to reflect this condition.

We aim to compare the effect of 3-DOF haptic rendering to that of 6-DOF haptic rendering, and within the latter we also compare its effect when rendered on a fully-actuated (force and torque output) versus an under-actuated (force only) haptic interface. We use *sphere* rendering to refer to a 3-DOF method that computes haptic feedback through a sphere centered at the tip of the instrument (e.g. [12,13,14]). Our 6-DOF rendering algorithm [16] treats the virtual instrument as a full rigid body for collisions and contact, and we henceforth refer to it as *r-body* rendering. Our hypotheses are then:

H1 *R-body* haptic rendering improves task performance over *sphere* haptic rendering.
H2 *R-body* haptic rendering on a force and torque display improves task performance over rendering on a force-only display.

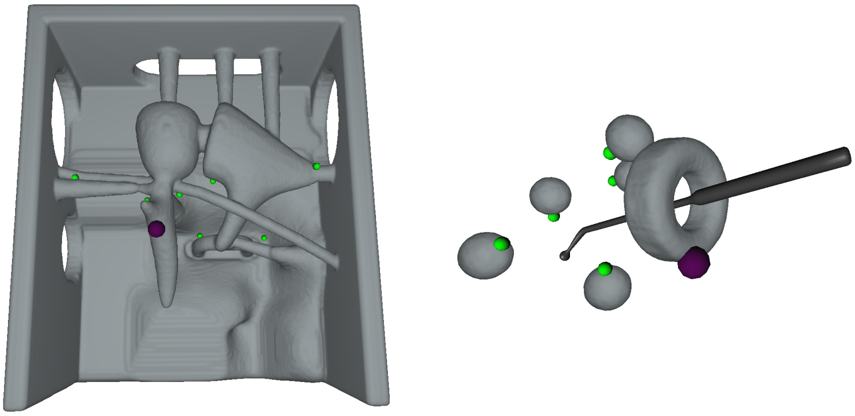
4. Methods & Materials

An experimental study with a within-group design was conducted to measure the effect of three variants of haptic feedback (sphere rendering, under-actuated r-body, and fully-actuated r-body) on task performance in two surgically-relevant virtual scenes. The presentation order of the two scenes, and then of the three haptic rendering variants within a scene, was randomized. The experiment, including a pre-study questionnaire and a semistructured debriefing interview, lasted 90 minutes. A five-minute break was mandated midway through the experiment.

One virtual scene used for the study was a model of middle ear anatomy (Figure 1a), inspired by our ongoing work in otologic surgery simulation. The other was a synthetic scene modeled to emulate similar constraints that may be encountered in other surgical procedures (Figure 1b), where the instrument must be passed through a small, round port. A number of small targets were placed at various locations within the scenes, and the task was to touch all of the targets (in any order) using the tip of a virtual probe while avoiding excessive contact with obstacles in the environment.

The three variants of haptic feedback were compared as the independent variable in this study. With sphere rendering, only contact with the tip of the probe results in force feedback. The subject would experience no additional haptic feedback if the shaft of the instrument were to collide with obstacles in the environment. With r-body rendering, under-actuated display is emulated on the same 6-DOF haptic device by simply discarding the computed torques, thus controlling for differences of other device characteristics.

Task performance was measured in terms task completion time and the number of errors made. An error was defined as exceeding 5 mm of incursion of the instrument into another structure. In all variants, we provided a form of sensory substitution (or “visual haptics” [2]) by coloring the probe yellow for small penetrations (>2 mm), then



(a) "Ear" scene. Model of middle ear anatomy. (b) "Port" scene with a narrow corridor.

Figure 1. Virtual environment scenes used in the study. The objective of the task is to touch all the small spherical targets using the virtual probe instrument shown in (b).

orange (>3.5 mm), and finally red when the error threshold is exceeded. To complement measured performance, perceived performance was captured by a questionaire and a semistructured interview.

4.1. Apparatus

A stereoscopic 3D virtual environment was created to conduct the experiment. Within the environment, the subject controls and manipulates the virtual probe instrument using a Phantom Premium 1.5/6-DOF haptic device (Figure 2). Virtual scenes were scaled (including the middle ear) to a size of roughly 20 cm to fit the workspace and spatial resolution capabilities of the device. Stiffness of haptic rendering was set to 500 N/m of displacement. Torsional stiffness for 6-DOF interaction depends on the inertia of the virtual instrument, and amounted to approximately 1.8 Nm/rad for the probe. Visual feedback was provided in stereoscopic 3D through an LG 32" television with passive circular polarizing glasses. Task completion time and number of errors made during each trial were automatically recorded by the software application.

4.2. Procedure

Twelve subjects (8 males, 4 females aged 19-41, mean 25) participated in the experiment. One subject was left-handed, for which the virtual scenes were mirrored. Five subjects were medical students and four have had clinical experience. Subjects were compensated with two movie tickets for their participation.

Subjects were instructed on the use of the haptic interface, first within the manufacturer's test application, then in an unscored pre-study scene in our application, until they were familiar with haptic exploration procedures and force feedback. The subjects were given written instructions of the task including instructions to complete the task as quickly and with as few errors as possible. In addition, the instructions reassured that no error would be recorded for contact resulting in a warning (yellow or orange) level, and that the participant should explore error boundaries during the practice sessions.

(a) Experimental setup showing the Phantom Premium 1.5/6-DOF haptic device and 3D television.

(b) A subject's grasp of the device handle and the corresponding virtual probe instrument.

Figure 2.

Each subject completed multiple measured trials of the task in both scenes and with all three variants of haptic feedback. The subject was asked to practice under each condition for about four minutes or until s/he felt ready. Then the subject repeated the task for five minutes while measurements of time and errors were taken. An average of 8 trials per condition were recorded for every subject.

A written questionnaire was administered after each condition session. Perceived difficulty was measured as the sum of the answers to two 7-degree Likert scale questions, one regarding the difficulty of hitting the targets and the other of avoiding collision with the surrounding environment. Perceived benefit of haptic feedback was also measured on a 7-degree Likert scale as the answer to the question, "Did you perceive that the haptic feedback was assistive in helping you to complete the task?" The experiment ended with an interview regarding the participant's experience of the haptic feedback variants.

5. Results

Analysis of the data with paired t-tests (all having $df=11$) showed significant differences between sphere and r-body rendering. Apart from perceived performance, no significant differences between fully-actuated and under-actuated display were observed.

5.1. Task Performance

The analysis was based on comparing the average of each subject's result for one condition and scene with the same subject's average result for each of the other two conditions (within-subject, paired t-test). The average for all measurements is reported in table 1.

Task completion was significantly faster with r-body rendering compared to sphere rendering using both the fully-actuated (t=7.0, p<0.001) and under-actuated (t=7.8, p<0.001) display in the port scene. No significant time differences were found in the ear scene. Significantly fewer errors were made with r-body rendering compared to sphere rendering using both the fully-actuated (t=6.5, p<0.001) and under-actuated (t=6.6, p<0.001) display in the port scene as well as the ear scene (t=3.8, p=0.002; t=3.3, p=0.003 respectively). No significant differences were found between fully-actuated and under-actuated display in terms of completion time or errors for either scene within a 95% confidence interval.

Table 1. Mean values and standard deviation of task completion time (sec.), errors, and questionnaire results concerning perceived difficulty (range 2-14) and perceived benefit (1-7). *U* indicates under-actuated display.

	port scene			ear scene		
	sphere	r-body^U	r-body	sphere	r-body^U	r-body
Task completion	39.5 (12.2)	27.0 (7.8)	23.9 (9.1)	43.3 (16.3)	40.8 (13.8)	38.7 (8.9)
Task errors	5.3 (3.9)	0.8 (1.3)	0.6 (1.2)	2.8 (2.5)	1.3 (2.0)	0.9 (1.2)
Total measurements	88	118	136	81	84	88
Perceived difficulty	11.3 (2.2)	7.0 (2.7)	5.6 (2.3)	9.1 (2.5)	7.5 (3.6)	6.5 (2.0)
Perceived benefit	1.9 (1.5)	4.4 (1.2)	5.1 (1.2)	2.5 (1.0)	4.1 (1.3)	4.8 (0.8)

5.2. Perceived Performance

The task was perceived to be significantly more difficult with sphere rendering than with r-body rendering using the fully-actuated display in the ear scene (t=3.9, p=0.001). In the port scene, the sphere rendering was perceived to be more difficult than the r-body rendering using both fully-actuated (t=8.0, p<0.001) and under-actuated display (t=7.7, p<0.001). Whatmore, using the fully-actuated display was perceived as less difficult than the under-actuated display (t=2.3, p=0.022). Percevied benefit was significantly higher for r-body rendering compared to sphere rendering using both the fully-actuated (t=4.4, p<0.001) and under-actuated (t=4.4, p<0.001) displays in the port scene, as well as in the ear scene (t=6.7, p<0.001; t=3.2, p=0.004 respectively).

The interviews revealed that all subjects recognized the difference between sphere and r-body rendering, but only some could tell or articulate any difference between the fully-actuated and under-actuated display. One participant described that the fully-actuated variant *"felt more smooth when I brushed the tool over the surface, but I could not really tell (...) it felt like it gave more graded feedback."* Others perceived the fully-actuated rendering to give harder or earlier feedback. One subject particularly liked the fully-actuated rendering: *"There was something about [it] that made it make a little bit more sense, a little bit more intuitive. Maybe it was the resistance on it, maybe something else."* However, another subject felt that there was something *"weird"* with the fully-actuated variant and thus preferred the under-actuated r-body rendering which *"felt to me like I had lot of control. Maybe it had a slower response in how I rotated it. This one [fully-actuated] I felt was too fast and too hard to control."*

6. Discussion

The results of our study show that 6-DOF haptic rendering, where the full geometry of the virtual instrument is used for collision detection and contact handling, allows subjects to complete an instrument positioning task in a constrained virtual environment with fewer errors and sometimes faster. In addition, the task was clearly perceived as easier and the user experience superior to that provided by 3-DOF haptic feedback.

Subjects performed the poorest with the sphere-based haptic rendering even though visual warnings were provided before an error was made. This may indicate that sensory substitution of this form is inferior to real, high-fidelity haptic feedback. Apart from user experience, no significant difference in performance was observed between under-actuated and fully-actuated display. The use of fully-actuated devices may still have a greater effect when applied to other tasks, or with more complex geometry. A greater contribution may also become apparent when using higher-fidelity devices, such as those with improved inertia, friction, or stiffness.

A surgical simulator that provides the user with a realistic visuohaptic experience is postulated to be of utility as a rehearsal or teaching environment for rare or technically difficult surgical procedures. The results of our study motivate 6-DOF haptic rendering as a valid approach for simulation of dexterous manipulation tasks, such as those encountered in many types of surgery, regardless of whether or not torque can be displayed.

7. Acknowledgments

This research was supported in part by NIH Grant R01-LM010673 and the Department of Veterans Affairs, Veterans Health Administration, Office of Research and Development, Rehabilitation Research and Development Service. The authors thank Eva-Lotta Sallnäs Pysander of the Royal Institute of Technology for her valuable feedback on study design.

References

[1] P. Ström et al., Early exposure to haptic feedback enhances performance in surgical simulator training, *Surgical Endoscopy* **20** (2006), 1383–1388.

[2] O. A. J. van der Meijden, and M. P. Schijven, The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: A current review, *Surgical Endoscopy* **23** (2009), 1180–1190.

[3] L. Panait et al., The role of haptic feedback in laparoscopic simulation training, *The Journal of Surgical Research* **156** (2009), 312–316.

[4] M. K. Chmarra et al., Force feedback and basic laparoscopic skills, *Surgical Endoscopy* **22** (2008), 2140–2148.

[5] H. K. Kim, D. W. Rattner, and M. A. Srinivasan, The Role of Simulation Fidelity in Laparoscopic Surgical Training, In Proc. *MICCAI* (2003), 1–8.

[6] K. S. Lehmann et al., A prospective randomized study to test the transfer of basic psychomotor skills from virtual reality to physical reality in a comparable training setting, *Annals of Surgery* **241** (2005), 442–449.

[7] P. H. Cosman et al., Virtual reality simulators: Current status in acquisition and assessment of surgical skills, *ANZ Journal of Surgery* **72** (2002), 30–34.

[8] C. R. Wagner, N. Stylopoulos, and R. D. Howe, The role of force feedback in surgery: analysis of blunt dissection, In Proc. *IEEE Haptics Symposium* (2002), 68–74.

[9] S. Wang, and M. A. Srinivasan, The role of torque in haptic perception of object location in virtual environments, In Proc. *IEEE Haptics Symposium* (2003), 302–309.

[10] L. N. Verner, and A. M. Okamura, Force & torque vs force only feedback, In Proc. *IEEE World Haptics* (2009), 406–410.

[11] R. Weller, and G. Zachmann, User Performance in complex bi-manual haptic manipulation with 3 DOFs vs. 6 DOFs, In Proc. *IEEE Haptics Symposium* (2012), 315–322.

[12] M. Agus et al., Real-time haptic and visual simulation of bone dissection, *Presence* **12** (2003), 110–122.

[13] D. Morris et al., Visuohaptic simulation of bone surgery for training and evaluation, *IEEE Computer* (2006), 48–57.

[14] P. Trier et al., The visible ear surgery simulator, *Studies in Health Technology and Informatics* **132** (2008), 523–525.

[15] F. Barbagli, and K. Salisbury, The effect of sensor/actuator asymmetries in haptic interfaces, In Proc. *IEEE Haptics Symposium* (2003), 140–147.

[16] S. Chan et al., Constraint-based six degree-of-freedom haptic rendering of volume-embedded isosurfaces, In Proc. *IEEE World Haptics* (2011), 89–94.